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Acoustic Emission Studies of Bearing Failure in Composites

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Abstract

Superior structural performance of composites has been widely known to the aircraft industry for a long time now. The availability of advanced composite materials and a wide variety of material forms have attracted aircraft designers to adopt composites for the development of large primary and secondary aircraft structures. This growth of composites technology has necessitated improvements in quality assurance during both manufacturing and in-service. Traditionally, the role of Non-Destructive Testing in quality assurance has been limited to defect detection. With advances in technology, Non-Destructive Testing has evolved into a multi-disciplinary science and has a critical role in ensuring quality and reliability. Of all the available Non-destructive Testing techniques, Acoustic Emission (AE) is probably the only technique that can be applied for monitoring damage initiation and propagation in real-time. Researchers have verified AE as a successful technique for detecting different micro-failures and their acoustic signatures as they occur in laminated composites.

For the limited series production of SARAS aircraft, the wing is proposed to be of carbon composite fabricated by the "VERITy-Vacuum Enhanced Resin Infusion Technology" method as against the conventional prepreg/autoclave method. VERITy is a variant of the VARTM process and aims at economical & faster production rates of composite aircraft components. The development of a prototype Wing Box by the VERITy method and its testing is considered a major step in the composite wing programme. The Wing Box has two crucial joints, the Skin Splice Joint & Spar Splice Joint. To gain confidence in following a new fabrication method and to validate the design of these crucial joints, feature level configurations of Skin Splice & Spar Splice joint were fabricated. A static test schedule was initiated to qualify these critical joints of the Wing Box. It was quite a concern to designers to obtain a realistic assessment of structural integrity of the joints during the structural qualification tests. In such a situation, AE was the immediate choice for the detection of any premature damage initiation and growth, in the new material system (HS Carbon UD fabric G0827/RTM 120 Epoxy Resin system) adopted to fabricate the wing. During the static testing of the Splice joints, resonant AE sensors detected significant AE activity originating at critical locations in the joints. The activity was indicative of some damage and subsequent post-processing in time domain was in-sufficient in identifying the nature of damage. It was important to identify the type of damage that had occurred and to provide reliable information towards the structural integrity of the joints. No correlation could be established with already available AE signatures for different kinds of composite failure. Hence, simulated tests on specially fabricated control specimens were *carried out to generate typical AE signature for Bearing failure. The AE activity acquired during testing of the control specimens was analyzed in both time and frequency domain. The characteristic feature of this data in terms of Event distribution, Amplitude & frequency content was the signature for Bearing failure. Based on this signature, the AE activity acquired during the testing of the Skin Splice & Spar Splice joints were analyzed. The characteristics of this AE data matched well with the signature generated on control specimens. Presented in this paper is a discussion on the characterization of AE activity from the Skin Splice & Spar Splice joints as Bearing failure at fastener holes.*

Keywords: *Composites, Bearing Failure, Acoustic Emission, Non-destructive Testing & Evaluation, Liquid Composite Molding(LCM).*

1. INTRODUCTION

Application of composites in the development of new commercial and military aircrafts has seen a phenomenal rise in the recent years, which is due to the fact that composites offer significant advantages over conventional metals. Composite fabrication incorporates technologies like Co-curing and Co-bonding that help in reducing the part count, joints and fasteners. Hence, the advantage is two-fold: avoiding stress concentration and shorter assembly time. Designers have two basic joining techniques for composites: adhesive bonding and mechanical fastening. In practical applications it is often unavoidable to resort to mechanical fastening due to strength requirements and to have periodical access to the interior of a structure. Mechanical fastening has generally been used for highly loaded composite components, although composites have low bearing stiffness that can lead to bolt bending and hole elongation under compressive loading [1]. Hence, the weakest parts of a composite structure are often the joints and it is well known that fasteners can severely reduce the load carrying capacity. Therefore, it is important that the strength and failure in composite joints be fully understood in order to design efficient and reliable load carrying joints [2,4]. Due to the anisotropy and in-homogeneity of composites, strength and failure of bolted composite joints can be considerably different from that of metallic joints. Damage in bolted composite joints can initiate at an early loading stage and accumulate inside the laminates as the load increases. The accumulation of damage and the mode of failure strongly depend on the material system, ply orientation, laminate thickness, joint geometry, loading condition, etc [3]. There are in general three basic macroscopic composite joint failure modes: Net Tension Failure, Shear-out Failure and Bearing Failure. Failure by the first two modes is catastrophic and results from excessive tensile and shear stresses. Bearing failure is a local compressive failure mode due to contact and frictional forces acting on the surface of the hole [4]. However, bearing failure is progressive, very complicated and is influenced by many parameters, including washer dimension and lateral clamping force [2,3,4,5]. Studies on the behaviour of bolted composite joints reported in literature indicate that in aircraft applications, Bearing Failure is an important failure mode which requires special attention.

Yi Xiao & Takashi Ishikawa [1] report that fibre micro-buckling, matrix cracks, delaminations and other forms of damage frequently serve as the 3D failure mode under compressive load in laminated composites. Their experimental investigations clarify that bearing failure processes are very complicated in bolted composite joints. Eriksson [2] has shown that bearing strength is influenced by several important parameters, including lateral constraint conditions and ply orientations. Wang HS et al.,[3] used bearing response and bearing strength of bolted joints to examine bearing failure mechanism as a function of clamping pressure. Wu & Sun [4] investigated the behaviour of pin-contact failure of composite laminates and found that fibre micro-buckling in the 0-deg plies of the laminate plays an important role in the initiation of bearing damage. Camanho et al.,[5] carried out a detailed experimental investigation for three basic failure modes of a joint, and their results show that the main mechanism of bearing failure is accumulated delamination damage. Park HJ [8] has reported the effect of stacking sequence and clamping pressure on the delamination and ultimate bearing strengths of mechanically fastened joints in composite laminates and the use of Acoustic Emission technique to detect the onset of delamination failure. Ireman T et al.,[9] have conducted experiments on composite specimens to measure and characterize the development of damage in the vicinity of fastener holes in mechanically fastened graphite/epoxy laminates. They have characterized the Bearing failure process (matrix cracking, fibre failure, delamination and kinking) in a composite joint with respect to percentage of failure load.

Aircraft components and structures are perhaps the most critical from the viewpoint of quality and reliability of performance. Their specific design requirements, material composition, manufacturing and functionality have to meet stringent requirements. Typical defect conditions that originate in a composite component during manufacturing or those developed during service can significantly reduce the strength & structural integrity and ultimately lead to failure. Early detection or monitoring is the key to provide critical information towards development of structural damage, which can be useful in initiating timely repair and maintenance. Non-destructive evaluation plays an unique role in terms of testing, diagnosis, inspection, qualification and monitoring of aircraft structures & components to achieve high levels of quality, safety and reliability of performance that spans over the entire life cycle of a component. Traditionally, tap tests and ultrasonic-based inspection methods have been used to inspect composite structures. But advances in NDT over the years have made it possible to reliably detect various defect conditions in composite structures irrespective of the construction.

2. ACOUSTIC EMISSION (AE)

Acoustic emissions are stress waves produced by the sudden release of strain energy due to micro-structural changes occurring in a material. As the stress waves reach the surface of the specimen, small out-of-plane displacements are generated which are detected by a piezoelectric transducer. The amplified signal is then conditioned, recorded and finally analyzed. Acoustic Emission (AE) is a Non-destructive Evaluation technique that can provide real-time information of the deterioration in structural integrity and early warning of defect growth towards failure in a structure. AE allows us to extend our hearing to detect sounds of higher frequencies and lower intensities and offers global monitoring that can cover large, often inaccessible areas of a structure. The distance of propagation depends on material properties, geometry, frequency and the environment. The main advantage of AE is that under real-time continuous monitoring, events may be detected as they occur and from any location in the structure being tested. There are two types of AE signals encountered in practice: Continuous & Burst Emissions. Continuous emissions are low energy stress wave bursts which are un-resolvable, i.e., they cannot be separated in time. These signals often include background noise due to mechanical and electrical disturbances. Burst or Transient emissions are individual stress wave bursts that have higher amplitude and energy. They can be separated in time and the beginning & end of these signals can be clearly identified. AE has been popularly used by researchers for real-time monitoring of damage development in composites: Delamination[Park, 2001], Matrix Cracking[W H Prosser et al., 1995] and damage development during tensile and compressive testing[Ireman et al., 2000]. Different types of micro-failures have been found to give different acoustic signatures, which are used to identify different types of damage as they occur in composites [6]. In general, AE is a remarkable tool for studying crack propagation, phase change, dislocation movements, material deformation, etc, as the information it provides is both detailed and immediate.

3. THE VERITY METHOD

To avoid the high costs associated with autoclave cured composite parts, the aerospace industry is looking for alternative cost-effective processing methods while maintaining the same high quality and performance of autoclave-cured components. In the last few years, Liquid Composite Molding (LCM) technologies have advanced to the point, where, they can provide that alternative and are also viable for aircraft production. *"Vacuum Enhanced Resin Infusion Technology – VERITy",* belongs to the family of liquid composite molding techniques and is a variant of the "*Vacuum Assisted Resin Transfer Molding – VARTM"* process. The VERITy method, developed and perfected at NAL aims at reducing manufacturing costs and can be readily applied for the fabrication of large aircraft structures that include primary and safety critical structural components. The fibre reinforcement (Hexcel HS Carbon UD Fabric G 0827 6 1040) also called "Preform", held in the tool cavity is injected with a resin system (Hexcel RTM 120 resin & HY 2954 Hardener) and differential pressure is maintained so as to completely wet out the fibre. The preform is sandwiched between the solid mold surface on one side and a vacuum bag on the other side. Vacuum is applied to draw the catalyzed thermosetting resin through the preform stack from strategically placed inlet ports. Once the resin saturated preform undergoes a cure temperature cycle, the composite part is ready to be removed from the mold. The variation in the VERITy process over other RTM processes is the use of autoclave for curing with the application of external pressure (1bar) and vacuum (760mm Hg) to achieve good compaction levels and optimum levels of resin volume. The potential advantages of VERITy are: relatively low production costs, low cost tooling, can be applied for manufacturing very large and complex parts, high fibre volume fraction (58-60%) can be achieved with low void content (<1%) and properties comparable to autoclave molding

4. SPLICE JOINTS OF THE COMPOSITE WING

For NAL's civilian aircraft "SARAS", it was proposed to develop a composite wing by the VERITy method, with aims of weight optimization and significant cost savings. To facilitate ease of assembly and to meet the required accuracies a three-segment wing concept was adopted, one center segment called the "Inboard" and two "Outboard" segments (LH & RH). The Left Hand (LH) wing and Right Hand (RH) wing individually consist of 23 stations, with station #1 situated at centerline of the aircraft and station #23 situated at the tip of both LH and RH wings. The central part "Inboard" extends from station #6 of LH wing to station #6 of RH wing as a single member. The "LH Outboard" and "RH Outboard" are two independent portions that extend from station #6 to station #23 on the LH and RH side respectively. Top and Bottom Skins of Inboard and Outboard portions are joined together at station #6 by means of Skin Splicing. Front and Rear Spars of Inboard and Outboard are joined together between stations #5 & #6 by means of Spar Splicing. The skins resist much of the Bending Moment in the wing and the Spars resist the Shear Force. Taking advantage of this concept, Skin Splice (Moment Joint) and Spar Splice (Shear Joint) are constructed at different locations instead of having them at the same location. This configuration would avoid the danger of weak joints at one point. To prove the design, it was necessary to ascertain the individual strength of the Skin and Spar Splice joints by conducting tests on an elemental level in the building block approach. Hence, appropriate portions of the Skin and Spar at the splicing points were chosen for fabricating the Skin Splice (Fig.1-a) and Spar Splice (Fig.1-b) joint configurations. These configurations were fabricated by the VERITy method and had similar geometrical features and thickness to that of the wing structure.

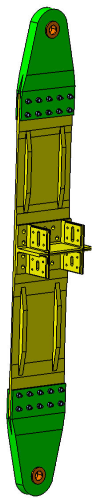

Fig. 1(a): Skin Splice Joint

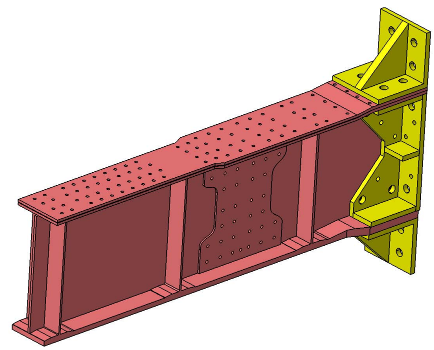

Fig. 1(b): Spar Splice Joint

5. STRUCTURAL TESTING OF SKIN AND SPAR SPLICE JOINTS

The Skin and Spar Splice joints are crucial as they are mechanically fastened features of the composite wing. The strength of the wing structure at the splicing locations had to be confirmed by conducting static tests on these joints which is a mandatory requirement for airworthiness certification. The Skin Splice joint consisted of a segment of the splice joint in the Bottom Skin. The Bottom Skin splice joint is selected, as it is more critical than the top skin splice joint. The Spar Splice joint consisted of a segment of the splice joint in the Rear Spar. The Rear Spar is selected as it carries more Shear Force than the Front Spar. Countersunk high tensile steel bolts were used to connect composite-to-composite and composite-to-metal parts in both the splice joint configurations. Both the joint configurations were subjected to Ultimate Design Loads (1.5 times the Limit Load) as per the Vertical Down case. The Skin splice joint was subjected to a maximum load of 176580N (Ultimate Load) and the Spar splice to a maximum load of 67369N (Ultimate Load). These loads simulated the actual stress levels expected at the splice joints in the wing. The load was applied using hydraulic jacks in steps of 10% and held at the ultimate load for 3 seconds and then unloaded back in steps of 10%. AE monitoring was carried out during both loading and unloading of the joint configurations.

5.1 AE Monitoring During Static Testing

The objective of carrying out AE monitoring on Skin and Spar Splice joints during static testing was to look for any premature damage initiation at the joints that might affect the structural integrity. Since a new fabrication process and material system was adopted to fabricate these test configurations, it was all the more important to assess the capability of these joints to sustain the ultimate design loads without a loss in structural integrity. Any damage that might initiate during the loading process would undermine the load carrying capacity of the joints and hence, AE was chosen to provide an early warning of damage if any and also help in identifying the nature of damage. The setup for monitoring AE during static testing consisted of the 20-channel MISTRAS-2001 AE system (Physical Acoustics Corp.), R15D piezoelectric sensors with a frequency range of 100-1000kHz and external pre-amplifiers were used to connect the sensors to the equipment. Two sensors were used for both the Skin and Spar splice joint configurations, which were located on the joints such that AE could be monitored around the fasteners on either side of the splicing for possible AE sources. Two sensors were sufficient to cover the area around the splicing. To minimize signal losses and improve surface contact, the sensors were smeared with couplant grease and then bonded to the Splice joints by metal caps. Prior to loading, the AE system was calibrated by the standard pencil lead break method at various locations on the joints, which also helps to check proper mounting of sensors.

6. RESULTS & DISCUSSIONS

The two sensors mounted on the Skin Splice joint began picking up significant AE activity from 60% load onwards until the maximum load of 150%. For the Spar Splice joint, the two sensors began picking up significant activity from 90% load onwards until the maximum load of 150%. As the intensity of the AE activity did not indicate any major concerns, the static testing was continued. The AE activity acquired during testing of these two joints were similar when analyzed in terms of typical AE parameters like Hits, Amplitude, Counts and Events. The pattern of AE data indicated a dense distribution of Events between 45-60dB, with a few sparsely distributed above 60dB. The maximum amplitude of a single Event for the entire distribution was 80dB and 93dB for the Skin and Spar Splice joint respectively, and a majority of the Event amplitudes were less than 60dB.

Waveform analysis of individual Hits indicated that a majority of the activity comprised of low amplitude "Continuous" emissions interrupted in between by a few discrete sudden "Burst" emissions of high amplitude. Each individual Burst was consistently seen overlapping with a successive "Burst" emission. On the whole, for the Skin and Spar Splice Joints, most of the AE data was dominated by low amplitude "Continuous" emissions accompanied by a few high amplitude "Bursts". This pattern of AE data and its nature were not readily discernible and could not be correlated with any other known composite damage signatures. Hence, definite conclusions on the nature of the activity and its source could not be arrived at.

After the test, based on detailed analysis it was felt that there were no chances of any major failure mechanisms to occur and the AE activity observed during the tests could be a result of Bearing failure at fastener holes. In order to verify this, a set of control specimen was specially fabricated using the same material system as that used for the Splice joints in which Bearing failure could be simulated. Each specimen was a composite lap joint, made from a VERITy laminate with a fastener at the center of the lap joint. The fastener was of the same kind and size as that used in the Skin and Spar Splice joint configurations. These control specimens were subjected to tensile loading in a "Zwick" Material Testing Machine to simulate Bearing failure at the fastener hole. The specimens were loaded in steps until failure, during which AE was acquired that served as the signature data for Bearing failure. Detailed parametric and waveform analysis of this signature data for Bearing failure revealed that it also comprised of very low amplitude "Continuous" emissions accompanied by a few high amplitude "Burst" emissions. The Bursts were again discrete and overlapped with a successive "Burst" emission. The low amplitude "Continuous" activity could be clearly distinguished from the high amplitude "Burst' signals. Hence, a good correlation could be established between AE signature for Bearing failure and AE activity from the Skin and Spar Splice joints.

Several researchers [6,7,10] have used AE to identify micro-failures in carbon fibre epoxy composite and discriminate them with respect to their frequency distribution. Bearing failure as reported in literature comprises of the following principal modes of failure: Matrix Cracking, Fibre-Matrix Debonding or Interfacial failure, Fibre Fracture, Matrix Splitting and Fibre Kinking [6]. A collective, stage-wise occurrence of all these failure modes is responsible for Bearing failure. To further characterize the signature data for Bearing failure and to compare it with the activity acquired from the Skin and Spar Splice joints, Joint Time-Frequency analysis was used. For this frequency domain analysis, a Joint Time-Frequency analysis package was developed using the Short Time Fourier Transform. This approach has been attempted to compare the AE signature for Bearing failure and the activity from Splice joints with those published in literature. Matrix Splitting and Fibre Kinking are considered to be macro-damage and are hence not considered in this analysis. For the Bearing failure signature obtained from control specimens, the low amplitude Continuous emissions correspond to low frequency bands from 50-180 kHz (Fig.2). The high amplitude Burst emissions display a wide distribution of frequency bands (Fig.3) ranging from 60-470 kHz. Similar frequency distributions were seen for the low amplitude and high amplitude Events of the AE data from the Skin (Fig.4 & 5) and Spar (Fig.6 & 7) Splice joints.

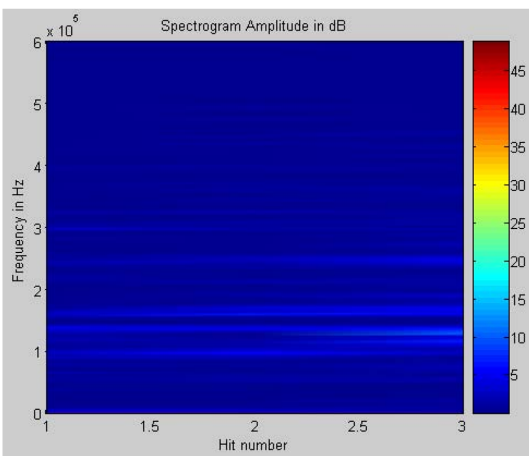

Fig. 2: Frequency spectra for Continuous Emissions of Bearing failure

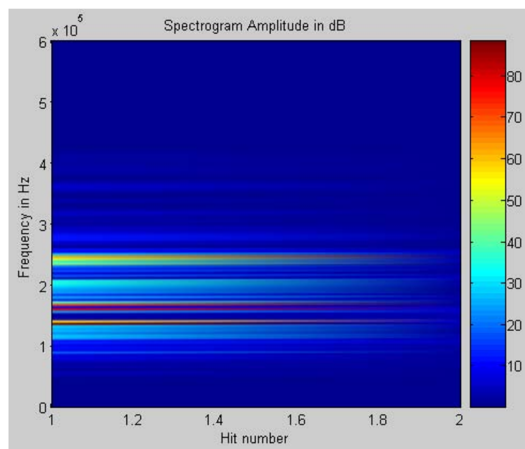

Fig. 3: Frequency spectra for Burst Emissions of Bearing failure

Most of the data reported in literature is consistent with Matrix Cracking related to frequencies in the range of 30-180Khz, Fibre Fracture in the range of 100-400kHz and Fibre-Matrix Debonding in the range of 200-450kHz. Groot et al.,[10] conclude from their study that Matrix Cracking related to frequencies between 90-180kHz, Fibre-Matrix Debonding between 240-310kHz and Fibre Fracture produced frequencies above 300kHz. Ujjin et al.,[6] conclude that matrix cracking produces low amplitude signals, Fibre-Matrix Debonding gives low-medium amplitude signals and Fibre Fracture gives medium-high amplitude signals.

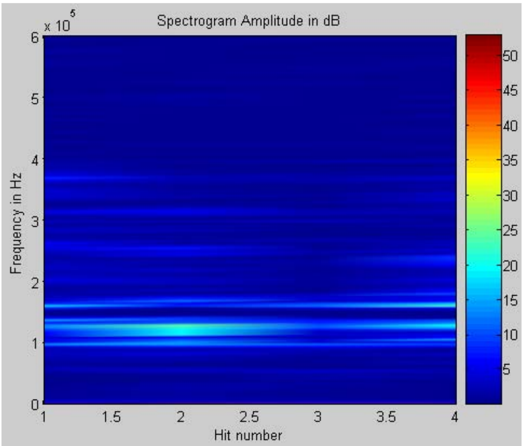

Fig. 4: Frequency spectra for Continuous Emissions from Skin Splice Joint

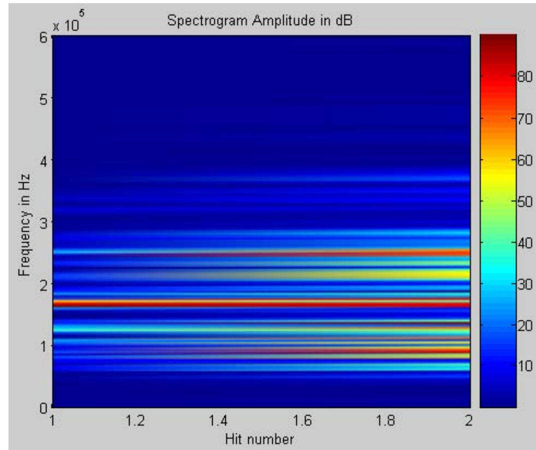

Fig. 5: Frequency spectra for Burst Emissions from Skin Splice Joint

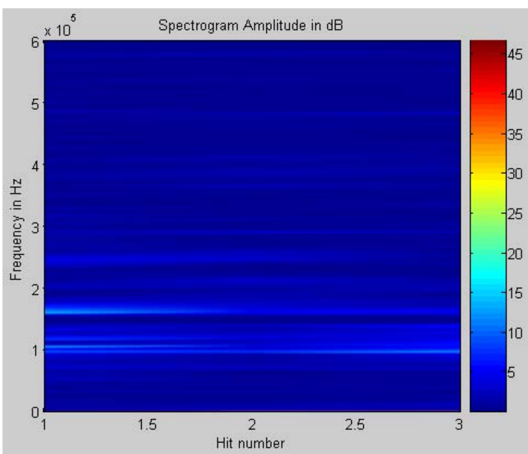

Fig. 6: Frequency spectra for Continuous Emissions from Spar Splice Joint

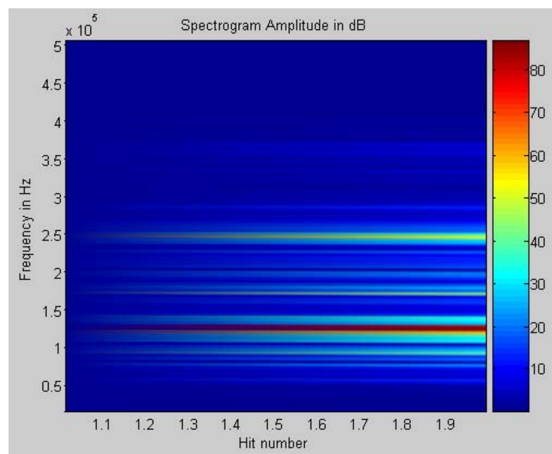

Fig. 7: Frequency spectra for Burst Emissions from Spar Splice Joint

The frequency distributions for Bearing failure signature and the AE activity from Splice joints agree well with data provided in the above sighted literature. Hence, based on conclusions of the above sighted references, the low amplitude Continuous Events are attributed to Matrix Cracking although some variations in amplitude may be seen due to dispersion and attenuation. The high amplitude Burst Events are attributed to Fibre-Matrix Debonding and Fibre Fracture.

7. CONCLUSIONS

The AE activity seen during the static testing of the Skin and Spar Splice joints has been successfully characterized as Bearing failure. AE Parametric and Waveform analysis have been helpful in comparing the AE activity from the Splice joints with signature for Bearing failure generated from control specimens. Joint Time-Frequency analysis has been beneficial in analyzing the AE data in frequency domain, the results of which are in good agreement with similar studies reported in literature.

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